Tampere University of Applied Sciences

Concrete Recycling:

A Surveyal of the United States from a Hazardous Materials Perspective

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Energy and Environmental Engineering

ABSTRACT

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As the construction continues to increase worldwide, there is a growing necessity to reuse material to minimize the environmental impact of the industry. One of the ways in which to do so might be to 3D print new concrete structures utilizing recycled concrete material with a focus on residential area sourcing. However, there are several hazardous materials that may be present in the material. This thesis aims to provide a framework of understanding of four key hazardous materials that may be present in the source concrete material used for recycling. The four key hazardous materials studied are asbestos, polychlorinated biphenyls or PCBs, hexabromocyclododecanes or HBCDs, and polycyclic aromatic hydrocarbons or PAHs.

For each of the four hazardous materials analyzed, the impact, prevalence, legislation, and mitigation information are presented. This was done by searching through several published article/journal database search engines for relevant information for each material and subtopic. Relevant information was collected, combined, and presented in a format that aims to present a holistic understanding of the materials and their potential impact on the overall viability of recycling concrete in the United States.

Ultimately, all four of the key hazardous materials are very detrimental to the health of people and environment and are widely prevalent in the United States. In order to ensure environmental safety, the concrete source should be tested for each of the hazardous materials, as ideally the source material wouldn’t contain any of the hazardous materials. For source material contaminated by a hazardous material, mitigation efforts should be utilized, if the material is to be used at all for recycling.

Key words: concrete, recycling, hazardous materials, asbestos, pcb, hbcd, pah

CONTENTS

ABBREVIATIONS AND TERMS

PCB	Polychlorinated Biphenyl
HBCD	Hexabromocyclododecane
PAH	Polyaromatic Hydrocarbon
USA	United States of America
US	United States
EU	European Union
ECHA	European Chemicals Agency
REACH	Registration, Evaluation, Authorisation, and Restriction of Chemicals (EU regulation)
EPA	Environmental Protection Agency
OSHA	Occupational Safety and Health Administration
ATSDR	Agency for Toxic Substances and Disease Registry
USGS	United States Geological Survey
POP	Persistent Organic Pollutant
TSCA	Toxic Substances Control Act
CAA	Clean Air Act
CWA	Clean Water Act

1 INTRODUCTION

As the world continues to develop and progress, more and more construction is done as buildings spring up worldwide. With this increase in construction, an immense amount of concrete is often utilized as one of the key building components. If the past is anything to go by in order to determine what the future holds, the need for concrete will increase, thus, recycling the material could be of great value in numerous ways. Construction waste continues to be a sizeable source of waste worldwide and therefore recycling certain aspects of that sector, sustainably and in an environmentally friendly manner, could prove to be very beneficial.

This report aims to highlight some of the potential concerns with recycling concrete, by surveying the topic from a hazardous material perspective. By gathering and presenting information on a few of the key hazardous materials prevalent in concrete, the viability of recycling concrete can both be better understood and potentially better handled from a more sustainable perspective.

The process of recycling concrete can vary based on the source of the input material as well as its intended final purpose. However, the process typically includes demolition, collection of the demolished concrete material, crushing and grading of the output to make recycled aggregate material, to create ready mix concrete, which can then be used for a new concrete structure. (Ganiron, 2015)

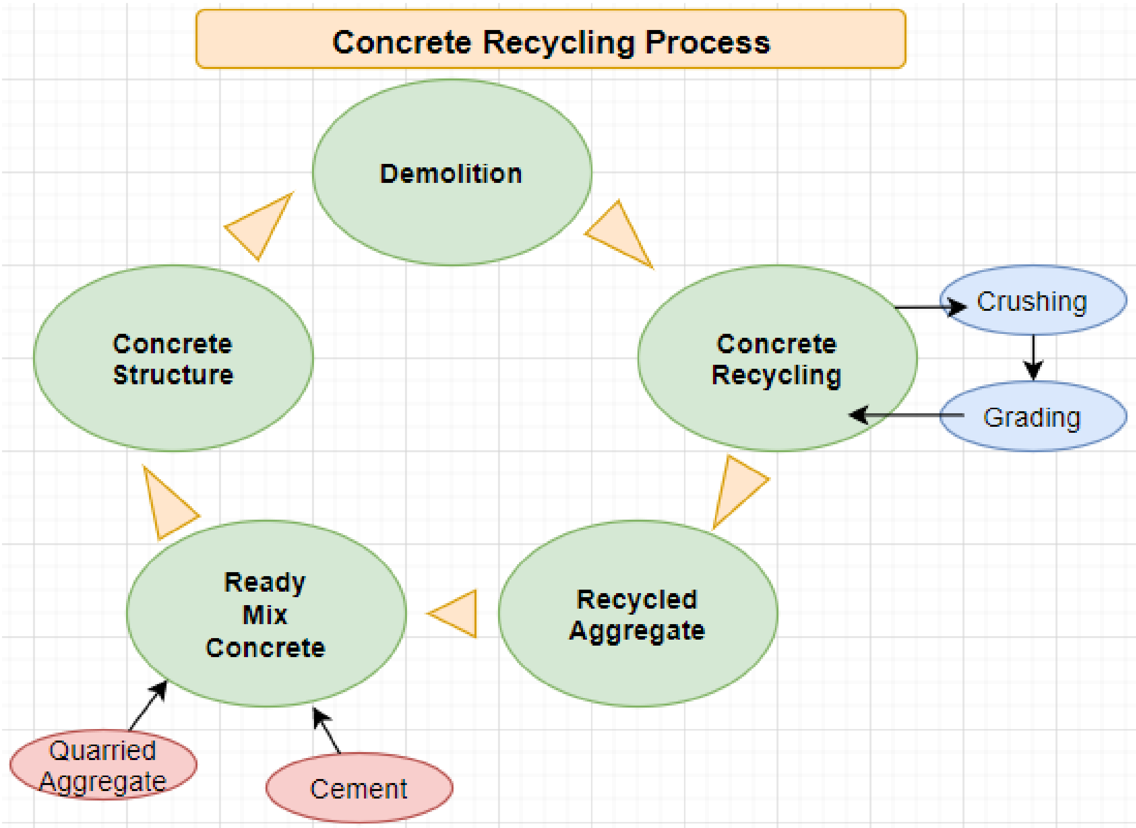

FIGURE 1. Diagram created to show the typical Concrete Recycling Process according to report by Van der Zee and Zeman (2016).

The figure above shows a simplified representation of the typical concrete recycling process, where demolished concrete material is crushed and graded into recycled concrete, cement and quarried aggregate is added depending on final purpose, to be made into a concrete structure. The percentage of recycled aggregate in the concrete mix causes different structural integrity properties but is not within the scope of this thesis. (Van der Zee & Zeman, 2016)

From a hazardous materials perspective, it is important to consider the demolition source, be it an old house, concrete piping infrastructure, etc. For the purpose of this report, the primary demolition source is considered to be demolished buildings as ideally demolished concrete material from residential areas could be utilized for 3d printing of new concrete structures.

The four hazardous materials this report will analyze are asbestos, polychlorinated biphenyls or PCBs, hexabromocyclododecanes or HBCDs, and polycyclic aromatic hydrocarbons or PAHs. Ideally the demolished material used for the recycling process would not include any of the listed hazardous materials, and as such the sourced material should be tested to minimize further environmental hazards.

Although this report will not go into detail on European Union (EU) legislation regarding these hazardous materials, the key EU governing bodies concerning these materials are the European Commission in tandem with the European parliament which proposes new laws and monitors implementation, the European Chemicals Agency or ECHA, which implements the EU regulation called Registration, Evaluation, Authorisation, and Restriction of Chemicals or REACH. (EC, 2021) It should be noted that many of the restrictions in the US and EU are similar, but there are some differences between the two.

2 SCOPE

This thesis aims to survey the viability of concrete recycling in the United States from a hazardous materials perspective. The key hazardous materials in concrete to be surveyed include asbestos, polychlorinated biphenyls or PCBs, hexabromocyclododecanes or HBCDs, and polycyclic aromatic hydrocarbons or PAHs. Their respective impacts, prevalence, relevant legislation, as well as potential mitigation information through the lens of the United States will be surveyed and presented in this report to provide a broad scale holistic understanding as to the viability of recycling concrete in the US.

3 METHODS / MATERIALS

This report aims to provide a holistic broad scale overview on the viability of concrete recycling from a hazardous materials perspective, and as such, information of some of the key hazardous materials that may influence the viability will be gathered and presented. For each hazardous material in this report, namely, Asbestos, HBCD, PCB, PAH, information as to their impact, meaning the harmful effects they potentially pose, their prevalence, meaning how widespread the material might be, legislation, meaning relevant laws pertaining to the material, as well as mitigation, meaning how one might approach reducing the influence of the material, will all be presented.

The majority of the search for the latest most relevant information to provide a holistic understanding of the hazardous materials was done through a number of published articles, thesis, and journal database searches such as the Directory of Open Access Journals in particular, for its accessibility, database, and worldwide collection of credible published material. Content available from the site is “licensed under a Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) license.” (DOAJ, 2021)

The key words used for the searches for information were the hazardous material name followed by the sections title to find relevant information for that particular part of the thesis. For example, to find relevant information on the impact of asbestos, “asbestos impact” was used as the search term. For the prevalence section, the search term included asbestos prevalence, asbestos statistics for example, in order to find appropriate relevant information depicting the prevalence of the hazardous material. For the legislation section, a similar search was done, except to include legislation as a key word, as well as a substantial use of the Environmental Protection Agency’s or EPA website, as the governmental site is one of the key facilitators and hosts the majority of the most up to date relevant information in laws pertaining to hazardous materials in the United States. For the mitigation section, the hazardous material followed by mitigation as a key search term was utilized to find a relatively new relevant mitigation method.

Asbestos was a primary focus for this thesis, and as such, the majority of the thesis will center around the material, but information will be presented on the other materials as well.

As a key priority for this thesis is to provide a broad view understanding of the four hazardous materials, the prevalence section was of particular importance. For the prevalence sections of the thesis where information was limited, or didn't provide an overview perspective of the material, alternative methods were sought out to present a holistic overview of the topic, nonetheless. For example, in the case of Asbestos, because of the vastness of its prevalence, data pertaining to home age in the USA was utilized to indicate an estimation of potential asbestos prevalence based on when asbestos was utilized from a historical perspective in tandem with the number of homes built in each decade over time. Although this method does not provide an exact number of asbestos contaminated homes, it could provide a sense of the scale of the issue. This method was also done for PCBs and HBCDs as well, to provide a sense of potential scale of the issue. It was not done for PAHs however, as PAHs can arise from a multitude of causes including burning wood through incomplete combustion which has occurred throughout the US for thousands of years.

Tables, charts and graphs were created when suitable to present information in a more succinct visual format.

Concrete recycling viability is dependent on a multitude of factors, many of which are not presented in this thesis. This report intends to provide rather a broad scale understanding of the materials potentially influencing the concept, thus the approach is presented from more of a macro scale than a micro scale.

4 RESULTS / DISCUSSION

This chapter includes the bulk of the hazardous material surveyal when considering the viability of recycling concrete. Each type of hazardous material is presented with some of the key aspects to consider, information that is relevant and useful to the topic, in order to provide a broad scope understanding of the environmental aspects that could potentially pose a threat in the United State of America. Presented is each hazardous materials' respective background information as to what it is, its impact – why it could be concerning, its prevalence – where is it pervasive, relevant legislation – what laws potentially influence the materials usage, handling, etc, and lastly, mitigation – how can its detrimental impacts be minimized. Where limited information is available, estimations and suggestions will be proposed utilizing available data. This ideally provides a decent summation of relevant aspects to consider for the audience to gain a holistic understanding of the important things influencing the viability of concrete recycling in the USA.

The Occupational Safety and Health Administration or OSHA is a US governmental organization that sets and enforces standards in the US. The limit values of eight-hour time weighted averages, meaning allowable exposure average amounts over eight hours, were obtained and presented in the table below. It should be noted that there are several types of some of the compounds, and certain ones may have different limit values according to both the EPA, as well as on the state level.

TABLE 1. OSHA limit values. Asbestos value (OSHA 2014), PCB value (EPA 2000), HBCD Value (EPA, 2018), PAH value (ATSDR, 1996).

Hazardous Material	**OSHA Limit Values**
Asbestos	0.1 fiber per cubic centi-meter of air (Eight-hour time-weighted average)
PCB	1milligram/cubic meter of air (Eight-hour time-weighted Average)
HBCD	Not yet established
PAH	5milligrams/cubic meter of air (eight hour time-weighted average)

These limit values must be abided by under US law.

As the environmental legislation is annually codified, environmental law concerns in the US should be directed to Title 40 of the code of Federal Regulations also known as 40 CFR according to the EPA.

4.1 Asbestos

Asbestos is a material with numerous valuable chemical and physical properties for several industries. Some of those properties include its “inexpensive, virtually indestructible, chemical resistance, bacterial resistance, incombustibility, thermal/electrical insulating ability, mechanical strength, flexibility, as well as friction and wear characteristics” (Banks, 1991)

There are four main types of asbestos, their properties can be found in the table below. However, for the purposes of this hazardous material report they will all be referred to under the term “asbestos” as the hazardous threat they pose, particularly in terms of the viability of concrete recycling, is fundamentally the same.

TABLE 2. Four main Asbestos types, information according to The NPS Institutional Archive (Banks, 1991)

Type	Description	Pros	Cons	Source	Uses
Chrysolite or White Asbestos	Fine silky flexible white fiber	Strength flexbility, heat resistance	Destroyed by acid	Canada, Russia, Rhodesia	90% of world production
Amosite	Brittle grey to brown fiber	Heat and corrosive resistance, elasticity	N/A	South Africa	Heat insulation, fire resistant insulation board
Crocidolite or Blue Asbestos	Needle-like blue fiber	Strongest asbestos fiber, acid resistance	Fuses at high temperatures	South Africa, Australia, Bolivia	Asbestos-cement pipe, marine insulation
Anthophyllite	Brittle white fiber	Heat resistance, excellent acid resistance	N/A	Finland, Africa	Expensive filler, specialized applications

From these materials, an industry was born utilizing the capabilities the fibers' properties enabled.

TABLE 3. Asbestos industry key developments over time with data from USGS report (Virta, 2006)

Year	Historical moment
1868-1869	First U.S Use of asbestos in roofing felt and cement
1878	Asbestos paper first made in the United States
1899	Wet Machine process of making asbestos cement
1904	Flat asbestos-cement board manufactured in the US
1906	Asbestos first used as brake lining
1929	Asbestos-cement pipe industry began in the US

As noted in table 3, the asbestos industry is over one hundred years old. Some of the first uses in the US include the use of asbestos in roofing felt and cement as early as 1868, and in paper in 1878. This is notable, as it marks some of the earliest beginnings of the usage of the material, and therefore allows for further analysis as to the prevalence it has throughout the USA, so that when considering the viability of recycling concrete, there is a deeper more thorough understanding as to the potential existence of the hazardous material in concrete material to be utilized for recycling. Another notable point on the timeline is in 1904 flat asbestos-cement board was manufactured, brake lining soon thereafter. In 1929 the asbestos cement pipe industry began in the US marking the beginning of an era where across the US water supply and waste lines were increasingly using asbestos-cement pipe. (Virta, 2006)

Although the asbestos industry began modestly in the 19th century in the textiles industry, it rapidly grew in the 20th century as it proved to be a valuable material in a multitude of large-scale industries. It was widely used for such a time that its current prevalence throughout the USA may impact the viability of recycling concrete as it may contaminate source material which could pose a hazardous threat both now and into the future.

4.1.1 Impact

Although asbestos has numerous beneficial properties for a number of industries, it can be particularly detrimental to human health or even fatal. If exposed to the fibrous material, it can get lodged in the lungs and lead to a range of severe consequences.

“Asbestos is one of the key occupational carcinogens as about 125 million people worldwide are exposed to asbestos in the workplace, and at least 107,000 people die each year from either lung cancer, mesothelioma and asbestosis as a result of asbestos exposure.” (CMR, 2019)

If asbestos fibers are inhaled, it can lead to different detrimental health consequences. Under high dosages for short periods of time, one may experience an acute inflammatory response. Under low dosages and prolonged exposure, a chronic inflammatory response may occur which leads to inflammation of the lungs potentially leading towards cellular and DNA damage (CMR, 2019). Cancer cells can then be developed, and the exposure can end up being fatal.

One of the aspects of asbestos caused diseases that makes it particularly potent yet difficult to control, is the fact that typically most people do not show signs of the disease until well after initial exposure. More than 10 to 40 years can pass from initial exposure to symptoms of disease to appear. (CMR, 2019)

Although the size of the asbestos fibers inhaled is accepted to have some impact on the likelihood of severe health impacts, it is also safe to assume no amount of asbestos exposure is safe for one's health (CMR, 2019). By this notion, it is of great importance to minimize its prevalence through mitigating its proliferation when considering the viability of recycling concrete, not to mention serious precaution must be taken when handling the material.

4.1.2 Prevalence

It is difficult to accurately find accurate data on the true scale for which asbestos is prevalent in the United States. The substantial widespread usage of asbestos as a near 'perfect substance' for decades before the eventual decline of its utilization beginning in the 70s does not allow for complete, precise data measurements on exactly how much and where exactly asbestos is present today. However, based on the datapoints that *are* available, rough conclusions can be drawn as to its prevalence, namely - how much, as well as by location – on a macro scale (national level) and to some degree, the micro level (prevalence in the home).

One important aspect to consider to gain a sense of the scale of asbestos contamination is the usage in asbestos cement pipe throughout the water infrastructure in the US. "In the US and Canada, it's estimated that more than 600,000 miles of asbestos cement pipe are in use." (Williams & Von Aspern, 2008)

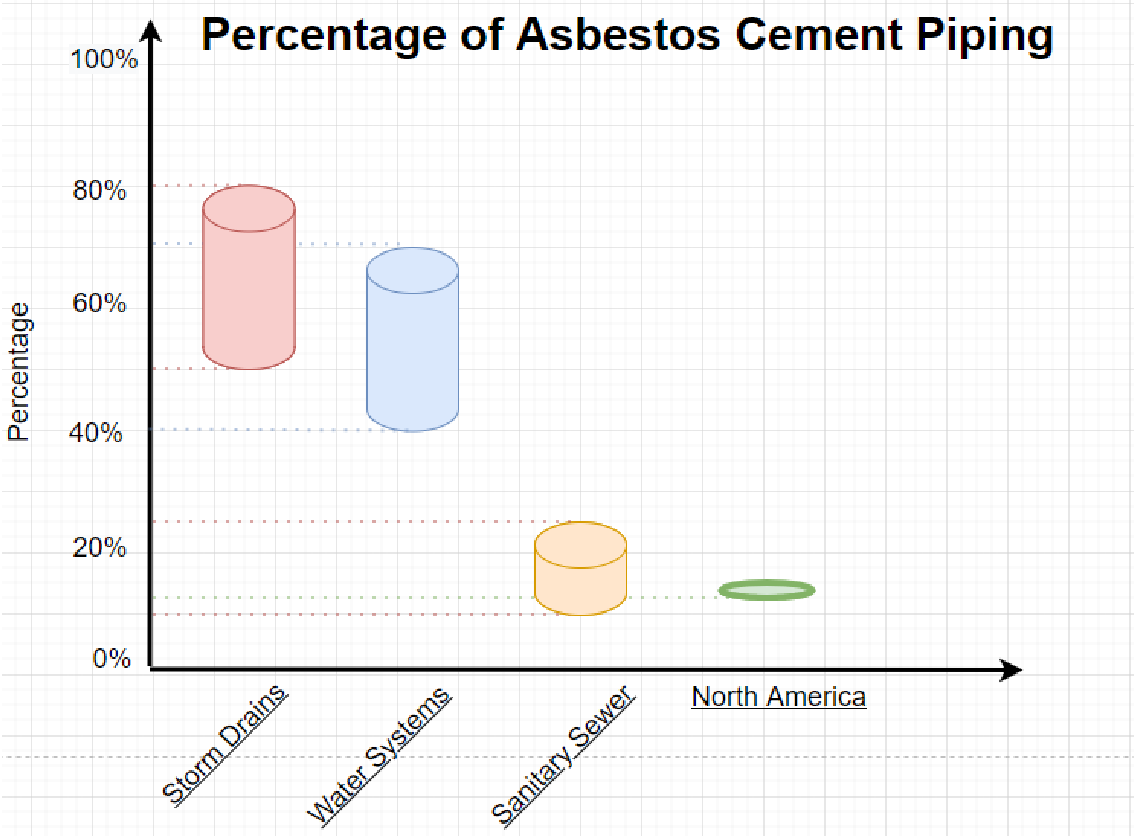

FIGURE 2. Percentage of water/storm drainage pipes using asbestos cement piping in the USA and Canada with data from HDR Engineering (Williams & Von Aspern, 2008)

The figure above shows the estimated percentage of water or storm drainage piping made of asbestos cement. According to the research Williams and Von Aspern conducted, asbestos cement piping makes up 50-80% of the storm drain systems, 40-75% of the water systems, and 10-25% of the sewer systems and an overall 15% of the water infrastructure system on a national average in the USA and Canada. This hints at the macro scale prevalence of asbestos nationwide, and some serious consideration must be done particularly if the concrete recycling source material is piping or has been exposed to piping.

The second way to consider asbestos prevalence in the US is through data on its prevalence in the American home.

TABLE 4. Potential Asbestos sources in a typical American home according to asbestos.com (Whitmer, 2021)

A) Exterior Surfaces	**E) Textured Paint**	**G) Appliances**
Roof felt and shingles	Boilers, Heating & Piping	Refrigerators/freezers
Window putty	Heat source Covering	Range Hoods
Cement Asbestos board siding/undersheeting	Door Gaskets	Woodstoves (Heat Reflectors
B) Insulation	Duct Linings	Clothes Dryers
Vemiculite insulation	Wall Gaskets and Linings	**H) Micellaneous**
Batt Insulation	**F) Electrical Equipment**	Fireplace logs
C) Flooring	Recessed Lighting	**I) Automotive**
Vinyl Asbestos FloorTile	Wiring Insulation	Brake Linings
D) Interior Surfaces	Fuse Boxes	Gaskets
Popcorn/sprayed on Ceilings	Outlets	Clutch Facings

As noted in table 4, asbestos can be widely prevalent throughout the home. Everything from roof shingles to siding, tiles to popcorn ceilings could potentially contain asbestos. It is important to consider what the source material utilized for the concrete recycling process may have been exposed to, as well as whether or not asbestos may have thereby contaminated it. This is particularly relevant when considering sourcing material from residential areas or from demolished homes.

Over the years, asbestos usage has changed quite a bit, both in terms of its total amount used, but for what purpose as well. Based on data from the USGS publicly available, a table was created to represent usage over the years to demonstrate how the main purposes for its usage has changed over time.

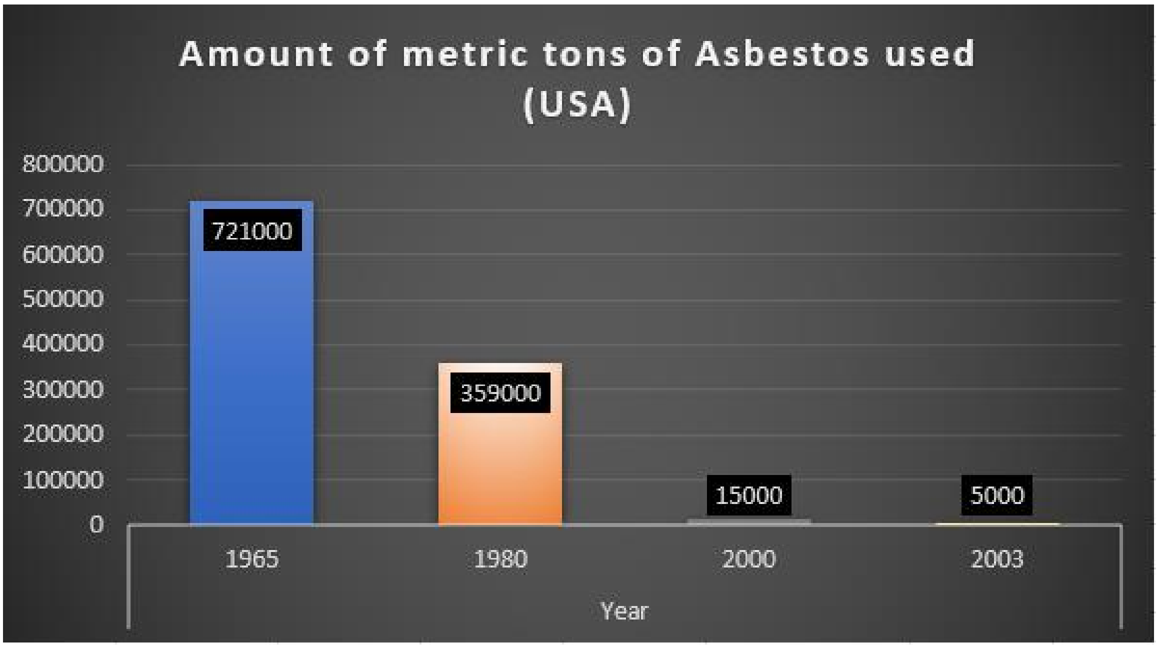

FIGURE 3. Amount asbestos of used, in metric tons, in the US by year

Figure 3 demonstrates the drastic reduction in total amounts of metric tons of asbestos utilized in the USA over time, for years for which will be further investigated below. Asbestos was a highly prized material in a multitude of different products over the years, but as shown above, went from a staggering 721,000 metric ton value in 1965 to a relatively negligible amount of 15,000 metric tons in 2000 and 5,000 metric tons in 2003.

Table 5. Usage type of asbestos in US in Consumption by % by year. Data points retrieved from the USGS report. (Virta, 2006)

Usage Type	Consumption in % By Year			
	1965	1980	2000	2003
Flooring	25,0	19,5	0	0
Asbestos-cement pipe	19,0	11,7	0	0
Roofing	10,0	6,7	60	60
Friction products	8,9	14,5	13,3	0
Asbestos-cement sheet	6,9	6,4	0	0
Electrical Insulation	1,5	1,7	0	0
Thermal Insulation	1,5	0,8	0	0
Packing	3,0	1,7	0	0
Gaskets	3,0	1,7	20	0
Paper	2,0	0,3	0	0
Textiles	2,0	0,3	0	0
Coatings	0,3	1,6	1,7	12,5
Compounds	0,3	1,6	1,7	12,5
Plastics	0,3	0,3	1,7	0
Other Uses	20,0	30,9	1,7	15
Amount of metric tons used	721000	359000	15000	5000

(*Cells with 0 refer to that usage type having amounts less than 500 tons - essentially negligible values.)

The data for usage types was actively collected beginning in 1965, therefore the data for years prior to 1965 is unavailable. Although data for total consumption amounts of asbestos over the years is available, the usage statistics is not. It should also be noted that this table represents the types by percentage of that years respective total. In the year 1965, there was limited fear or apprehension towards the asbestos product, and it is visible through the numbers presented, in that there is a wide spread of usages ranging from flooring to textiles to insulation. Flooring at 25%, asbestos-cement pipe at 19% and roofing at 10% were among the greatest areas of consumption by percentage in that year, not to mention the category of “other” usage. The “other uses category consists of end uses not falling into the other categories.” (Virta, 2006)

In 1980 there was certainly more apprehension towards the product as legislation had begun to fall into place restricting its presence, as well as an increasing public awareness towards the products hazardous properties. Flooring remained one of the largest consumption areas at 19.5% as well as asbestos-cement pipe at 11.7%, with an increase in friction products by percentage to 14.5% of consumption, with “other” uses consisting of 30% in 1980. The change from 1965 to 1980 in terms of percentage of total consumption is largely due to increased regulation, public awareness, and products shifting towards minimal usage of asbestos or at least towards products that might have a smaller exposure risk.

According to the data in table 5, in the year 2000, percentage consumption of asbestos increased to 60% for roofing, friction products listed at 13.3% and gaskets to 20% of asbestos consumption for that year. For many of the usage types, there was less than 500 tons reported for that type and therefore according to the USGS was effectively unaccounted for. Thus, even if a cell lists 0 it does not necessarily mean there was 0 use of asbestos for that type that year, just that its use was less than the minimum requirement of 500 tons for that type to be listed that year. The increase to 60% for roofing in this year more so presents the idea that there was a dramatic shift in what asbestos was used for from 1985 to 2000, rather than an increase in total amount of asbestos in roofing, as total amount of asbestos continually decreased in the USA during that time period.

In the year 2003, the last year for which the USGS report of 2006 data presents a similar 60% of total asbestos usage in the United States remained in the roofing category, with usage in gaskets being effectively reduced to negligible, while coatings and compounds categories increased to 12.5% respectively. Again, it should be noted that total asbestos consumption was still decreasing over time.

From the Table created from key statistics gather from the USGS report, a graph was produced to show key aspects in a visual manner.

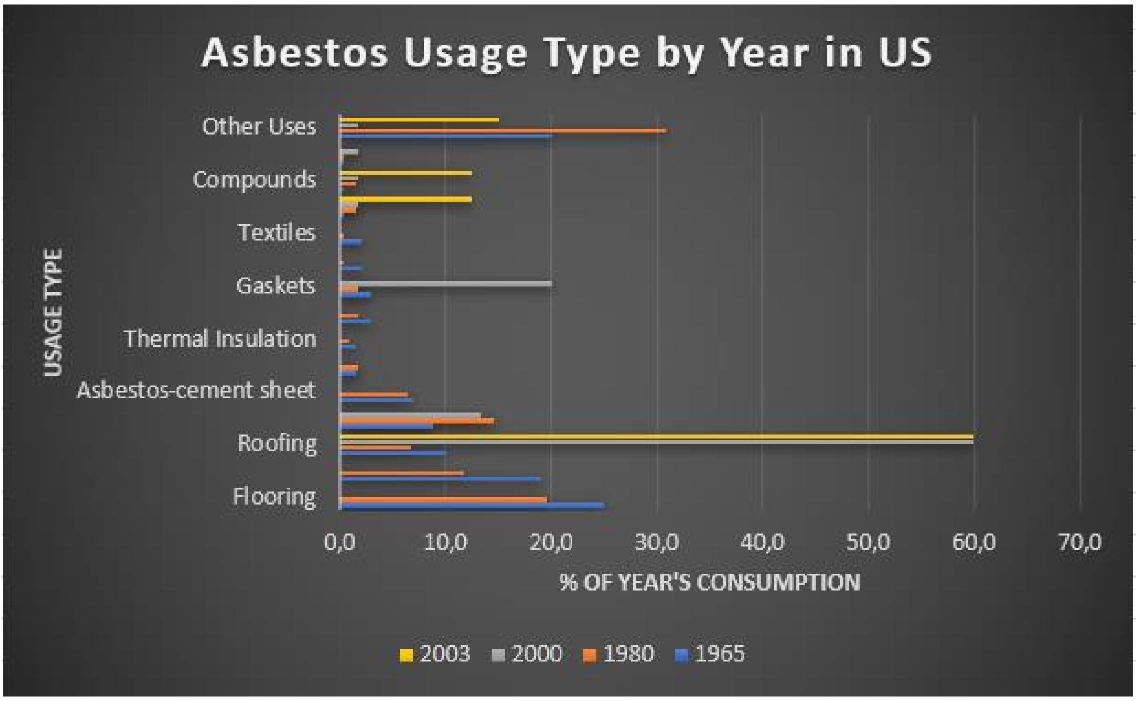

FIGURE 4. Key usage types of asbestos products by percentage of total asbestos usage by year.

In figure 4, the key asbestos product types are listed with their respective percentages of usage by year. Depending on the year, different types were more prevalent as far as percentage makeup of asbestos product usage, but the key types include flooring, roofing, asbestos cement sheet, insulation, gaskets, textiles, as well as other uses. It is also visible how the product types were more spread out in the earlier years of 1965 and 1980, where the orange and blue bars do not have quite the peaks that the years of 2000 and 2003 have. This indicates a widespread usage through a wider range of products in the earlier years as opposed to the narrower range of products containing asbestos in the later years surveyed. In particular, a peak of 60% of asbestos containing products of the years of 2000 and 2003 were under the roofing category, whereas the peaks of the years 1965 and 1980 were just 25% flooring and just over 30% for “other” respectively. This data could be utilized to roughly gauge the likelihood of asbestos presence in a certain part of the home, to better deem whether a source for concrete recycling may or may not be contaminated with asbestos exposure.

It should be noted that the older the home, or really any building for that matter, the greater the prevalence of asbestos is likely to be, as the utilization of asbestos in building materials was much more common throughout the middle of last century. It is less likely to be prevalent in newer homes or buildings as its presence in the latest building products has been effectively phased out.

When considering the viability of recycling concrete, this should be taken into consideration, as asbestos debris could end up in the concrete resource utilized for recycling.

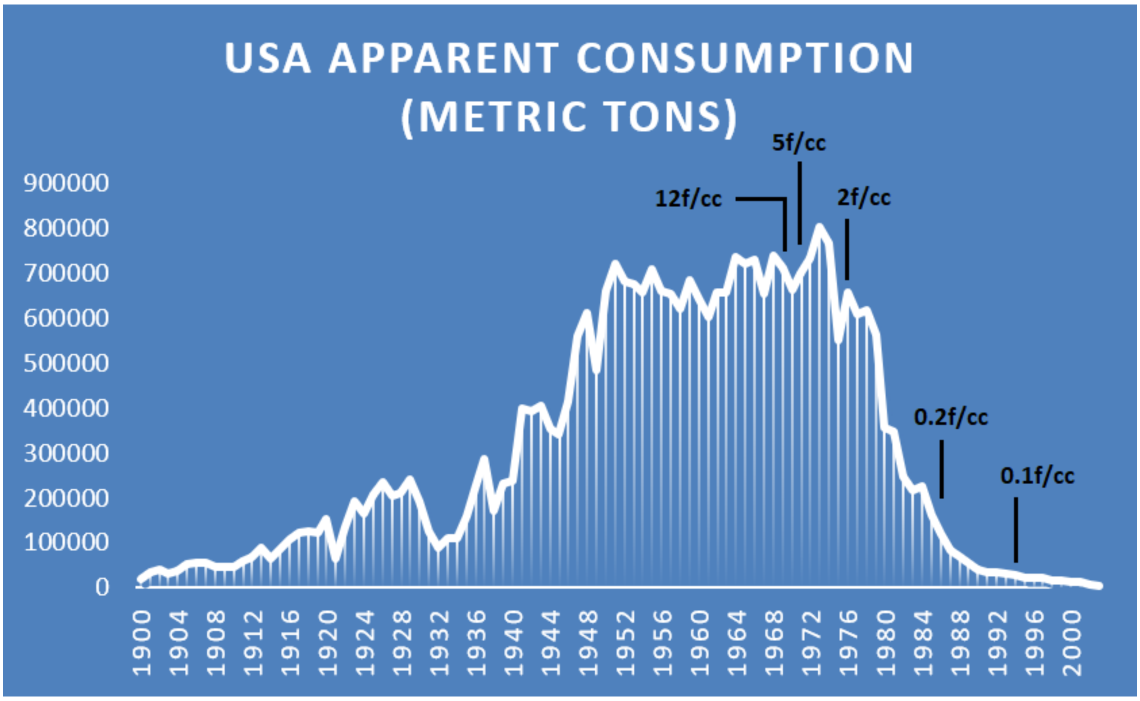

FIGURE 5. Asbestos use in metric tons, as well as the Occupation health and safety administration's or OSHA exposure limits – "12 fibers per cubic centimeter of air 1971, 5 fibers in 1972, 2 fibers in 1976, 0.2 fibers in 1986, 0.1 fibers in 1994" (CDC.gov 2009)

The figure above depicts the rise in asbestos usage during the 20th century, "peaking at 803 metric tons in 1973 before decreasing to 1,700 metric tons in 2007." (CDC.gov, 2009) Added to the graph are markings to indicate in what year OSHA limit values were decreased to what value in fibers per cubic centimeter. (CDC.gov, 2009) It also shows how the OSHA exposure limits were lowered over time largely due to increased information on the severity of exposure to asbestos. In any case, a significant amount of asbestos was used during the 20th century. According to the USGS Report, between 1900 and 2003, the total “apparent consumption”, which refers to total production plus imports minus exports, was 31,505,850 metric tons of asbestos. (Virta, 2006)

A third method to present the macro scale prevalence of asbestos on a nationwide level can be roughly linked to other more widely available, more detailed data points such as the prevalence of health defects caused by the presence of asbestos.

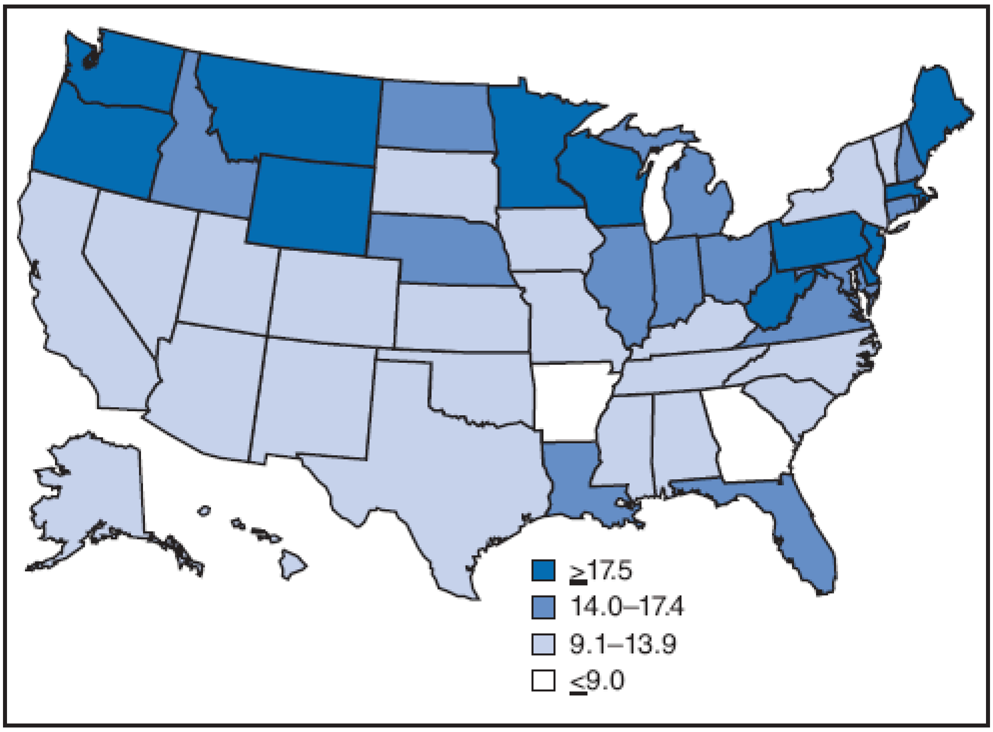

FIGURE 6. Mesothelioma death rates per 1million population by state 1999-2005 (CDC.gov, 2009)

The figure above shows the Mesothelioma death rate per one million population by state. Mesothelioma is primarily caused by exposure to asbestos, and 8 in 10 people with the disease have been exposed according to studies. (ACS, 2018) It should be noted that the map presents a per one million population rate, thus, a state with a high population like California would require a much higher number of cases to have a similar rate as a less populous state like Alaska. It shows a relative rate of exposure more so than an accurate depiction of colour coded depiction of Quantity – or number of total cases. Mesothelioma is a disease caused by asbestos exposure and can therefore, however roughly, suggest the prevalence of asbestos, as the disease is caused by the substance itself. The figure above would suggest there is a substantial presence of asbestos in many of the northern states, as well as in the New England area.

It should be noted that mesothelioma develops over time, and exposure to asbestos does not guarantee a mesothelioma diagnosis and even less so death due to that specific disease. It could, however, with relative accuracy confirm the presence of the material. Essentially, places with mesothelioma deaths confirm exposure, but the exact degree of prevalence is harder to obtain from this specific type of analysis.

Another way to consider the widespread prevalence of asbestos in the United States comes from asbestos mortality figures, namely asbestos related deaths according to death certificates.

The Environmental Working Group created a map that displayed occurrences of asbestos related deaths according to death certificates, namely mesothelioma and asbestosis between 1979 and 2001. (EWG, 2004) From the map, a few speculative conclusions could be drawn. Asbestos was widely utilized throughout the country, with an increased prevalence in larger metropolitan areas along the west coast, the east coast, in large cities spread across the Appalachian region, and much of the Midwest. Considering asbestos related diseases often only occur years after initial exposure, paired with the fact that asbestos exposure often requires unsafe handling or through demolition/renovation, it can be presumed that asbestos is fairly ubiquitous throughout the US.

A fourth method to consider the prevalence of asbestos in the United States is to analyze the country by age of the buildings. One of the most readily available and perhaps effective methods to gauge building age is through the data on housing in the USA. Asbestos usage in the USA began in the early 20th century, picking up steam over the decades, peaking in 1973 as far as consumption is concerned, followed by a gradual decrease in usage after that peak through public awareness and new legislation. Data on the age of houses in the USA was collected from Statista, a site that has a database of millions of different statistics on a multitude of different categories. Although the database contained the number of houses built in the USA by decade going all the way back to 1700, the number of houses built prior to 1860 was effectively negligible for the purpose of this analysis, thus they were not included in the following data analysis. (Statistica, 2020)

TABLE 6. Number of homes built in the USA by decade.

Year built	Number of homes built
2010-2019	5795000
2000-2009	27054000
1990-1999	26651000
1980-1989	25191000
1970-1979	25836000
1960-1969	20206000
1950-1959	21377000
1940-1949	9567000
1930-1939	5419000
1920-1929	9234000
1910-1919	4350000
1900-1909	5296000
1890-1899	2967000
1880-1889	201000
1870-1879	103000
1860-1869	56000

The different decades and their respective number of homes built in the USA were then color coded based on the prevalence of asbestos in the market. The areas in red were labelled as such due to the high risk of potential asbestos prevalence in products as between the years of 1900-1979 as there was the greatest usage of asbestos during these years. Although the rise of asbestos utilization was more gradual than the color coding might imply, it nonetheless presents an estimate of asbestos risk. The decade of 1970-1979 was chosen as the last high-risk decade due to the legislation that caused the waning of asbestos usage in the USA during that decade. The decade of 1890-1899 was labelled medium risk as it was the very beginnings of the rise of asbestos and therefore had a lesser risk of asbestos usage than the decades that followed. The years of 1980-1999 were labelled as medium risk as the waning out of asbestos usage was also gradual, and therefore cannot be accurately labelled as no risk of asbestos presence, but nonetheless had a lower risk than the decades prior due to the aforementioned legislation. The decades prior and after the medium risk decades were then labelled as low risk as a separate category to the medium or high risk due to the relative unavailability of asbestos products prior to 1890, as well as the widespread phasing out of the product after 2000. Although this is a simplified model of asbestos prevalence it could hint at the presence on a nationwide scale.

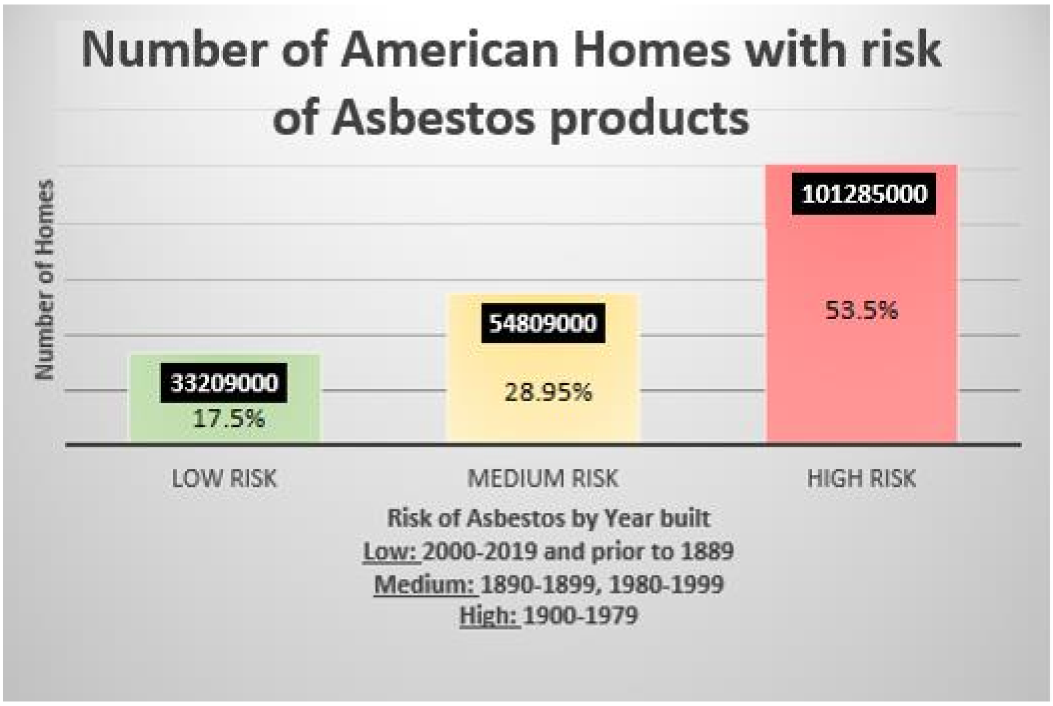

FIGURE 7. Number of American homes with risk of asbestos based on year built

In the figure above, over 50% of American homes, just over 100 million, have a relatively high risk of asbestos according to year built. Nearly 29% of American homes, at nearly 55 million, have a medium risk of asbestos according to year built, and only 17.5% or just over 30 million, of American homes have a low risk of asbestos according to year built. It should be noted that the houses built prior to the data set, namely homes built prior to 1860, were excluded from the analysis and would effectively only add to the low-risk category, as asbestos wasn't utilized during that time. However, the number of houses built prior to 1860 was relatively negligible in this data set.

All in all, asbestos is a widely prevalent material through the USA both in terms of product usages on a micro level, all the way to the grand scale macro level through a number of decades. This would suggest that with any consideration of concrete recycling, particularly where the material might be obtained from demolition or demolished structures, much consideration should be taken to the potential prevalence of asbestos.

4.1.3 Legislation

After links were made between asbestos and various diseases caused by the exposure to the material, as well as the increasing public awareness and opposition to the usage of the product, legislation was implemented to restrict the sale and use of asbestos. There are quite a few laws that have been put in place pertaining to asbestos in the USA over the years. Some of the most relevant will be discussed here.

“The Clean Air Act or CAA of 1970 classified asbestos as a hazardous air pollutant and gave the Environmental Protection Agency power to regulate use and disposal of asbestos, and spray applied asbestos products were banned.” (EPA, 2019) This is key legislation to consider when handling especially the disposal of asbestos as it could affect the viability of recycling concrete.

The Toxic Substance Control Act or TSCA of 1976 was one of the key laws passed pertaining to asbestos, as it provided the “Environmental Protection Agency the authority to place restrictions on certain chemicals such as *asbestos*, radon, and lead based paint. (15 U.S.C. § 2641-2656)” (EPA, 2019)

Asbestos usage has declined dramatically since the 1970s, only a few asbestos containing products are on the market, and asbestos is no longer mined in the USA. (EPA, 2019)

“In 1989 the Asbestos Hazard Emergency Response Act of 1986 or AHERA, made the EPA establish standards for inspecting and removing asbestos in schools.” (EPA, 2019) This could also be of valuable relevance to concrete recycling particularly if the source material has to do with comes from school foundations.

One of the latest legislative changes pertaining to asbestos was relatively recent. In 2019 a final rule "ensures discontinued asbestos products cannot be reintroduced without the agency evaluating them and placing necessary restrictions, including prohibiting use." (EPA, 2019)

The 2019 rule has some of the most relevant rules and regulations pertaining to concrete recycling as far as asbestos contaminant is concerned. The rule updates previous legislation and thus provides the most up to date and accurate information as to how to comply with the laws when handling asbestos.

According to the Environmental Protection Agency, the rule went into effect June 24, 2019, and promotes the Toxic Substances Control Act (TSCA) to ensure "any discontinued uses of asbestos cannot re-enter the marketplace without EPA review." This could imply recycling of concrete with asbestos contaminate must not occur without EPA review, and professionals must be certified to handle the material. (EPA Regulations, 2019).

The National Emissions Standards for Hazardous Air Pollutants or NESHAP, under direction from the EPA has rules regulating demolition and renovation aiming to minimize asbestos exposure through the air and must be abided by under federal law. (EPA Neshap, 2019)

Ultimately the material is quite heavily restricted, and before processing asbestos contaminated material, one should review and abide by the latest rules and regulations as well as state laws and guidelines as well.

4.1.4 Mitigation

Certified professionals should handle asbestos contaminated material according to OSHA and to abide by the standards they set. Ideally source material for concrete recycling should be tested and found to be contaminant proof if at all possible. Essentially all suspected asbestos containing source material should be lab tested for asbestos content.

In the case there is asbestos, specialists typically either remove the contaminant or seal it in. Either option would have a notable impact on the viability of concrete recycling if the asbestos is in or made contact with the source material.

One key mitigation method of particular relevance was a study done in Poland in 2018, in which a group investigated the viability of “obtaining aggregates from asbestos waste by the fusion process in the electric arc-resistance process.” (Kusiorowski, 2019.) The results obtained and presented in the report state the fibrous nature was destroyed and as was noted in the asbestos impact section, this is a major factor for the materials’ health impacts. This presents a promising potential of the viability of recycling asbestos contaminated source material for concrete recycling, but much more research would likely need to be done to scale up the process particularly considering the prevalence of asbestos in the USA.

4.2 Polychlorinated Biphenyl (PCBs)

Polychlorinated Biphenyls or PCBs “group of 209 congeners,” or biologically active chemical, that “have been designated as persistent organic pollutants or POPs by the Stockholm Convention.” (Kumar et al., 2012) The Stockholm convention on POPs is an environmental treaty restricting production and use of POPs.

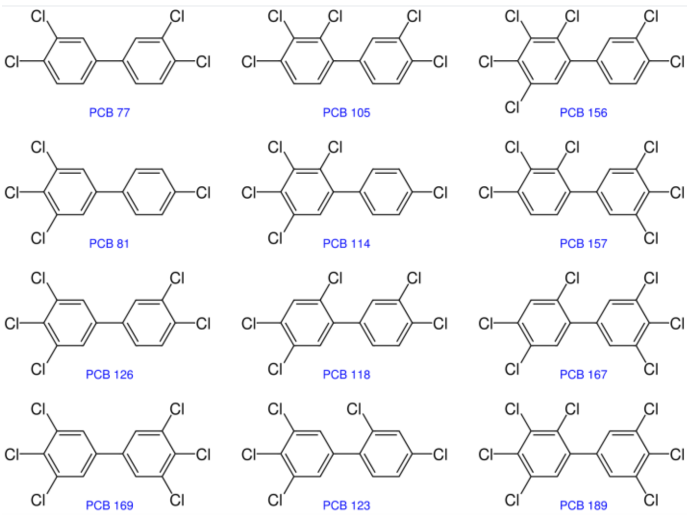

FIGURE 8. PCB’s atomic structure visualized (EnvironForensics, 2020)

They have been used in paints, elastic sealants for years, which can contaminate concrete structures and even the soil around buildings. Their non-flammable, insulating properties are particularly valuable for a number of different uses. (Almutairi, 2018)

TABLE 7. Commercial PCB Uses according to the EPA (EPA, 2021)

Commercial PCB Uses	
Thermal Insulation Material Fiber-glass,felt,foam,cork	Electrical equipment Voltage regulators,switches,re-closers,bushings, electromagnets
Caulking	Transformers and capacitors
Adhesives/Tapes	Old Electrical devices
Fluorescent light ballasts	Oil used in motors and Hydraulic Systems
Plastics	Cable Insulation
Floor finish	Oil-based Paint

Polychlorinated biphenyls were commercially manufactured from 1929 to 1979 when production was banned by the TSCA. However, some inadvertent generations of PCBs are allowed in excluded manufacturing processes. (EPA, 2021)

4.2.1 Impact

Polychlorinated Biphenyls are known to cause a multitude of negative health effects ranging from cancer to defects of the immune, nervous, reproductive, and endocrine systems. (EPA, 2021)

Studies in animals have proven PCBs to cause cancer, and there is increasing evidence suggesting it can cause cancer in humans as well.

According to the EPA, widespread studies suggest PCBs may have severe consequences to the immune system both in animals as well as humans. Studies also suggest negative reproductive effects in women in PCB factories, as well as fishing populations. The EPA also states a link between PCB exposure and neurological effects such as learning deficits in infants, as well as endocrine effects including hormone levels.

4.2.2 Prevalence

An estimated 1.5 million tons of PCBs were produced worldwide since the beginning of the manufacture of the product in the first half of the 20th century. (Tehrani & Aken, 2013) Exact information on the amount that was used in the US over the years is difficult to come by.
However, an estimated “70 million kilograms of PCBs were sold in the US between 1958 to 1971 for plasticizer use, such as rubbers, inks, textile coatings, and construction materials including caulk, adhesives, paints, and floor finishes.” (Almutairi, 2018)

Polychlorinated Biphenyls do not readily break down in the environment and remain prevalent in almost any normal setting for very long periods of time.

According to Almutairi Adibah, the lighter the PCBs, the further the contaminant can travel by water or air, while the higher chlorine content PCBs are “more likely to adsorb to organic matter in soils and sediments”. Due to the structure of the material, and namely its lipophilicity, it easily passes up the food chain furthering its movement and increasing its prevalence worldwide.

For these characteristic properties of the material, paired with its vast usage over the years, it is a potent contaminant that should be tested for when considering the sourcing of material for concrete recycling, particularly because it was widely used in and around the construction industry from caulking to paints which can seep into the porous material of concrete with relative ease.

“The mean atmospheric concentration of PCBs in urban areas in the USA was 5 nanograms/m^3 in 1992.” (WHO, 2003) The atmospheric concentration was typically slightly lower, but measurable nonetheless according to the World Health Organization’s report.

Based on the years PCBs were manufactured, an estimate on the number of US homes by risk of PCB contamination, namely, high, medium, and low risk was produced.

TABLE 8. Potential PCB contaminated homes in US based on PCB manufacture years vs home age. Green:Low risk, Yellow: Medium Risk, Red: High Risk

PCBs Manufactured between 1929-1978	
Year built	**Number of homes**
2010-2019	5795000
2000-2009	27054000
1990-1999	26651000
1980-1989	25191000
1970-1979	25836000
1960-1969	20206000
1950-1959	21377000
1940-1949	9567000
1930-1939	5419000
1920-1929	9234000
1910-1919	4350000
1900-1909	5296000
1890-1899	2967000
1880-1889	201000
1870-1879	103000
1860-1869	56000

In the estimation process, a transition period for the two early decades of PCB manufacture, as well as the two decades after the PCB ban was labelled as a medium risk for PCB contamination.

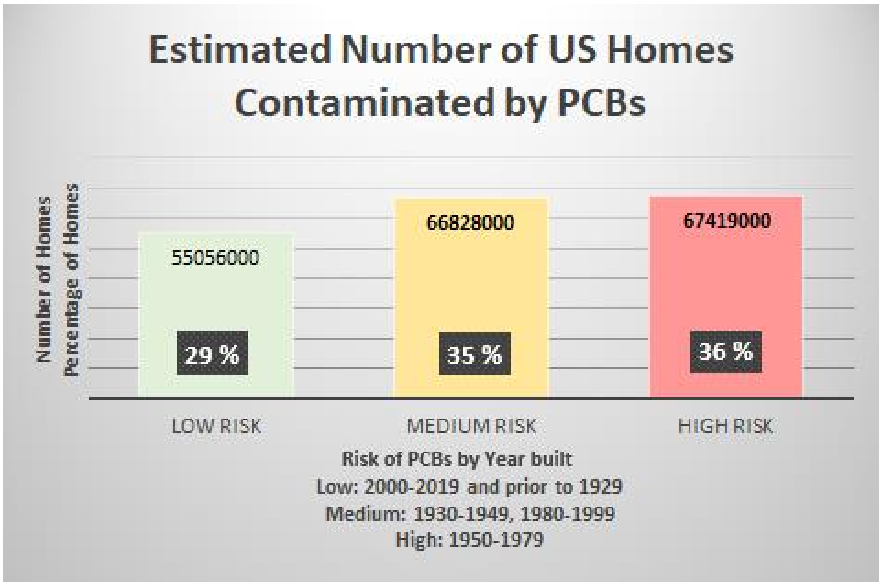

FIGURE 9. Estimated number of US homes contaminated by PCBs based on home age compared to PCB manufacturing years as well as percentage of total homes between 1860-2019 based on table 8.

Although this estimation is not necessarily accurate, it provides an estimation of the prevalence of PCB contamination on a residential level throughout the USA. It should be noted, however, that PCBs were not specifically used only in the residential sector, as much of the usage was for electrical insulation etc. PCBs are quite resilient in the environment on the other hand, paired with the fact that home renovations might include caulk usage containing PCBs and therefore could be even more prevalent than even this estimation suggests. In any case, the PCBs resilience in the environment and ability to leak into the porous material of concrete, it could influence the viability of concrete recycling in an environmentally friendly manner, and as such source material should be tested.

4.2.3 Legislation

The Stockholm convention on POPs is an international environmental treaty restricting production and use of POPs. It was signed in 2001 and went into effect in 2004. A total of 152 countries signed the treaty, including the United States of America, however it was not ratified by the USA. (UNTC, 2001)

The US failure to ratify the Stockholm Convention is due to the “lack of authority to implement all of its provisions.” According to the US Department of State. (USDoS, 2001)

However, through the Toxic Substances Control Act, or TSCA, “in 1978, Congress prohibited the manufacture of PCBs and severely restricted the use of remaining PCB stocks.” (EPA, 2009) According to the EPA it is categorized as a hazardous air pollutant under the Clean Air Act, or CAA, and a priority toxic pollutant under the Clean Water Act, or CWA. It should be noted that these are federal level laws, and there could be further restrictions and regulations on the state level.

4.2.4 Mitigation

Due to the widespread prevalence and resiliency of the PCB chemical mitigation of the material will be necessary in order to sustainably recycle contaminated concrete sources. According Adibah Almutairi's research, "utilizing reductive dehalogenation through zero-valent magnesium ball-milled with activated carbon in an acidified solvent system have shown PCBs can be broken down even in the presence of water." (Almutairi, 2018) The report goes on to state that the use of "acidified 2-butoxyethanol and zero-valent magnesium permitted the extraction and destruction of PCBs from contaminated building materials." (Almutairi, 2018)

The report suggests there are mitigation techniques that are potentially viable to extract and destruct PCBs from building materials, which could prove to be valuable in employing a sustainable environmentally friendly approach to recycling PCB contaminated concrete. However, one of the keyways in which to minimize the PCB content is physical removal of potential sources such as caulking prior to source collection.

4.3 Hexabromocyclododecane (HBCD)

Hexabromocyclododecane or HBCDs are a brominated flame retardant, a mixture of several isomers, primarily used in polystyrene and utilized for its thermal insulation capabilities in buildings. The two key products in which HBCD is utilized are extruded and expanded polystyrene foam or XPS and EPS, respectively. The worlds production of the material reached 16,700 tons in 2001. (Law, 2005.)

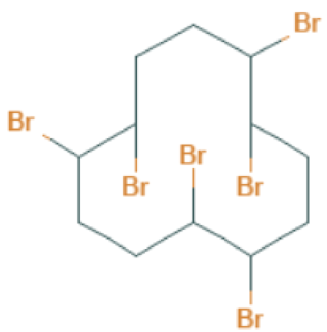

FIGURE 10. Hexabromocyclododecane atomic structure

Production of the compound began in the 1960s, and approximately 23,000 tons were being produced as of 2011. (InforMEA, 2011)

4.3.1 Impact

Studies have shown that repeated exposure to the substance for rats caused disruptions in the thyroid hormone system. (EPA Regulations, 2015) Although the compound is not quite as lethal per say as PCBs are for example, they still pose a hazard. Their prevalence in insulating material which can often flake easily can pose a harmful threat to those most vulnerable, namely infants, for which the primary method of harmful exposure is orally according to the EPA.

FIGURE 11. HBCDs warning labels (Pubchem, 2021)

Hexabromocyclododecanes pose a threat to the environment as they have been shown to produce detrimental effects in organisms such as algae, fish, and other organisms in soils. (EPA Regulations, 2015)

4.3.2 Prevalence

Due to the nature of the compound, both bioaccumulates and biomagnifies in the food chain according to the EPA. It is a persistent compound that can pass through generations, and as it travels up the food chain it poses more and more of a hazardous threat. It is categorized as a persistent organic pollutant or POP according to the Stockholm Convention due to the aforementioned aspects, as well as its ability to travel long distances. It should be noted however, that the USA is a signatory of the Stockholm Convention, but has not ratified it.

TABLE 9. Estimation of number of at risk of HBCD contamination US Homes by year built. (Red: High risk, Yellow: Medium Risk, Green: Low risk)

HBCD Values (1960-2009)	
Year built	**Number of homes**
2010-2019	5795000
2000-2009	27054000
1990-1999	26651000
1980-1989	25191000
1970-1979	25836000
1960-1969	20206000
1950-1959	21377000
1940-1949	9567000
1930-1939	5419000
1920-1929	9234000
1910-1919	4350000
1900-1909	5296000
1890-1899	2967000
1880-1889	201000
1870-1879	103000
1860-1869	56000

The table was created to represent an estimation of homes in the US potentially contaminated by HBCD based on year-built vs HBCD manufacturing era, thus High risk from the beginning of the HBCD manufacturing era of the 60s to 2009, medium risk for the decade after as well as prior, and low risk for all years previous.

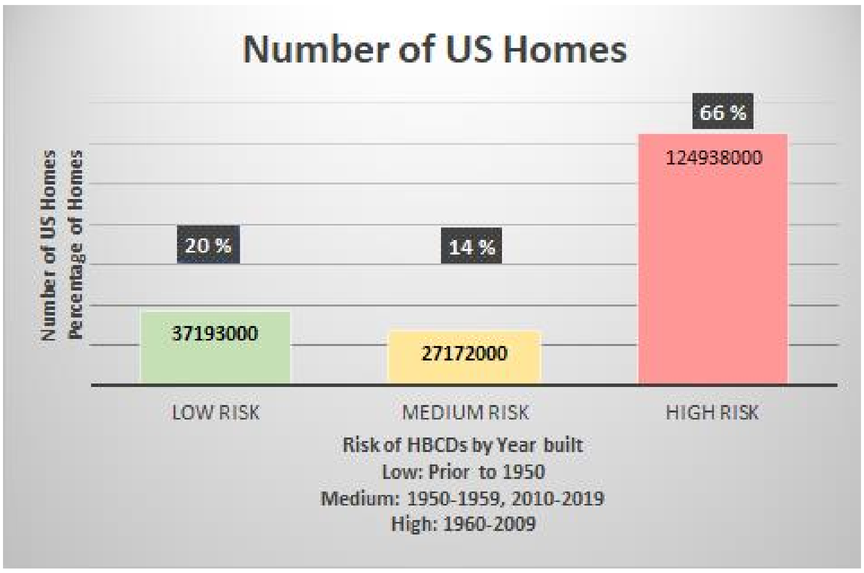

FIGURE 12. Number of estimated homes at risk of HBCD contamination by year built.

“An estimated 30,000 to 60,000 metric tons of HBCD were consumed in the US between 1988 and 2010.” (SCHF, 2017) Its primary uses consisted of building insulation in the form of foam insulation board.

As such, one of the primary ways in which the compound enters the environment is through construction and demolition, and thus if sourcing of concrete is from building demolition, measures should be put in place to minimize or eliminate potential exposure of HBCD from insulation foam board in particular to the source concrete material.

4.3.3 Legislation

Although the Stockholm Convention lists HBCD as a POP, the United States has signed the treaty, but has yet to ratify it. The US remains one of the few countries in the world that continues to produce the compound to this day. (InforMEA, 2011)

For a number of years, the only mention of HBCD in a regulatory context was under the flame retardant section of the Toxic Substances Control Act in 1976. (Law, 2005)

In the fall of 2020, the EPA released “the final risk evaluation for HBCD under the amended TSCA”. It states that HBCD presents “unreasonable risks to workers… from the use and disposal of HBCD in building and construction materials” (EPA HBCD, 2021)

The EPA now has a year to address the risks and could further implement prohibitory legislation restricting the substance. The exact legislation influencing the compounds usage could be subject to change in the upcoming years in the US.

4.3.4 Mitigation

Ideally the concrete source material would not be contaminated with HBCD from foam board insulation or other insulator material that may have been used in the original construction prior to demolition for source material. Depending on the scale of the contamination, the source material may need to be simply handled at a municipal solid waste incinerator. Tests should be done for HBCD compounds prior as to minimize the persistence and potential environmental contamination through the processing of such material, as there is little research proving viability of eliminating HBCD contamination of construction waste particularly in concrete, and as such demolition should be done with care as to minimize the potential of HBCD contamination to source material.

4.4 Polycyclic Aromatic Hydrocarbons (PAHs)

“Polycyclic aromatic hydrocarbons or PAHs are a group of chemicals that occur naturally in coal, crude oil, and gasoline.” (Munoz & Albores, 2011) When incomplete combution of organic material occurs, PAHs are released thus, they are very prevalent today both through natural means and human influence.

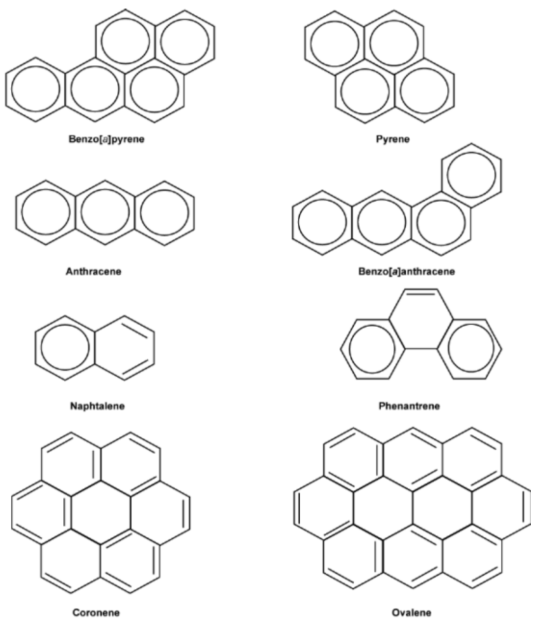

FIGURE 13. Structure of some polycyclic aromatic hydrocarbons or PAHs (Munoz & Albores, 2011)

With the increase in combustion of fossil fuels since the industrial revolution, PAHs emissions into the environment has increased.

4.4.1 Impact

Polycyclic aromatic hydrocarbons have the capability to influence the human DNA, causing adducts inducing oxidative stress resulting in mutations according to the report by Munoz and Albores (2011). This can then lead to an accumulation of mutations which can induce carcinogenesis or the formation of cancer.

PAHs are also known to cause a range of other detrimental health effects such as mutations, birth defects, death of fish, wildlife, and invertebrates. (Mahler, 2016)

4.4.2 Prevalence

Since polycyclic aromatic hydrocarbons exist naturally in gasoline, coal, and crude oil, paired with the fact that they are released during the burning of these products and others, PAHs are one of the most prevalent ubiquitous hazardous materials in the atmosphere worldwide. They are for the most part insoluble in water, but adsorb to soils, and particulate matter in the atmosphere which is the primary way in which they persist throughout the environment. They are more prevalent in urban areas than rural areas, largely due to the increased use and burning of fossil fuels. (Hyunok et al., 2010)

For the purpose of this thesis, the most relevant sources of PAHs that could affect the viability of recycling concrete would be sources that impact the construction and demolition sector. Some of they key sources of PAHs used in the industry include “tar products used for waterproofing on foundations and bathroom walls, treatment for roofing felt and tar paper, as well as in coal tar pitch which is used as a binder in asphalt, roofing and paving as well as a base for coatings and paint.” (Wahlström et al., 2019)

TABLE 10. Summarization of key PAH sources in construction industry according to Wahlström et al., (2019).

PAH Prevalence
Waterproofing Tar Products
Roofing Felt Treatment
Tar paper
Coal Tar Pitch (in Asphalt, Roofing, Paving)
Base for coatings/paints

In sourcing concrete for use of recycling, attention should be paid to the potential leaking of PAHs into the porous structure of concrete particularly from the aforementioned construction products.

FIGURE 14. Depiction of how PAHs can be gradually runoff into the environment (Mahler- USGS, 2016)

As shown in the figure above, a sealcoat product that contains PAHs dries providing a protective coating for the pavement. However, over time, the sealcoat can degrade through wear and tear and stormwater drains may carry PAHs through the runoff into the water basins, while the wind can move the chemical compound to the soils, and foot traffic can track it indoors.

4.4.3 Legislation

Certain polycyclic aromatic hydrocarbons are identified by the EPA, and ATSDR in the US due to various factors, but regarding the scope of this thesis, little is particularly relevant to the viability of concrete recycling.

The United States Environmental Protection Agency does require the reporting of any releases of PAHs exceeding one pound. (IDPH, 2020)

There are guidelines set by OSHA for the limits of exposure to PAHs on the worksite, through air for example, but no such federal level widescale bans, or hard restrictions to the polycyclic aromatic hydrocarbons as was the case for the other hazardous materials presented in this report.

The site for which the material sourced for concrete recycling should nevertheless be tested for PAHs in order to minimize the potential furthering of environmental hazards by way of polycyclic aromatic hydrocarbons.

4.4.4 Mitigation

Due to the nature of how PAHs spread and persist in the environment, it is quite difficult to eliminate the compounds, or even to minimize their presence.

One study suggests that the removal of PAHs from water by electrospun nanofibrous polycyclodextrin membranes is highly efficient. The researchers prepared a membrane that was then utilized to remove several PAH compounds from the water sample at a over 85% efficiency suggesting the viability of PAH removal from water sources. (Celebioglu et al., 2019)

Physical washing of source material that is contaminated by PAHs may just be the most effective method to attempt to minimize its presence. The contaminated wash could then potentially be treated with a relatively high success rate.

5 CONCLUSION

There are a multitude of factors to realize when considering the viability of concrete recycling for new building material for 3D printing in the United States, from asbestos prevalence and handling to polychlorinated biphenyls, not to mention the very real impact legislation can potentially have on every step of the process, both federal as well as state levels. Ultimately, it is important to consider that many, if not, most buildings in the United States built or even renovated before 1975 are likely to contain levels of asbestos which could then affect the viability of recycling concrete sourced from residential areas. It is also notable to consider that many buildings built or renovated between 1950 and 1979 are likely to contain PCBs in some form, on some level. These two components have the most stringent legislation concerning them and should be considered accordingly. Removal of caulk for PCBs, roofing tar for PAHs, insulation for Asbestos, polystyrene for HBCDs, and other potentially contaminated aspects of the source will most likely have to be concluded before any recovery of concrete waste for recycling can be environmentally retrieved. Ultimately, laboratory testing for the different toxic compounds should be conducted in order to abide by legislation; particularly at the state level which can be more stringent, as well as to minimize potential environmental concerns particularly in the future.

All four of the key hazardous materials are very detrimental to the health of people and environment and are widely prevalent in the United States. In order to ensure environmental safety, the concrete source should be tested for each of the hazardous materials, as ideally the source material wouldn’t contain any of the hazardous materials. For source material contaminated by a hazardous material, mitigation efforts should be utilized, if the material is to be used at all for recycling.

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